# 14

# Water Resources Management

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# CONTENTS

# EXECUTIVE SUMMARY

Water availability is an essential component of welfare and productivity. Much of the world's agriculture, hydroelectric power production, municipal and industrial water needs, water pollution control, and inland navigation is dependent on the natural endowment of surface and groundwater resources. Changes in the natural system availability would result in impacts that generally are greatest in regions that are already under stress, including currently arid and semi-arid areas, as well as areas where there is considerable competition among users. The purpose of water resources management is to ameliorate the effects of extremes in climate variability and provide a reliable source of water for multiple societal purposes. This evaluation of climate-change impacts focuses on the expected range of changes in the hydrological resources base and the sensitivity of the water supply and water demand components of the water management systems to climate change. It also makes an assessment of the viability of adaptive water management measures in responding to these impacts.

There are reasons for water resources managers, especially in developing nations, to be concerned by the results of climate-change scenarios, which show that the freshwater resources in many regions of the world are likely to be significantly affected. In particular, current arid and semi-arid areas of the world could experience large decreases in runoff—hence posing a great challenge to water resources management. Global-change-induced perturbations may follow widespread periodic and chronic shortfalls in those same areas caused by population growth, urbanization, agricultural expansion, and industrial development that are expected to manifest themselves before the year 2020 (High Confidence).

Uncertainties require considerable investment in research in order to improve prediction and adaptive responses. Some uncertainties in assessing the effects of climate change on water resources are:

- Uncertainties in general circulation models (GCMs) and lack of regional specification of locations where consequences will occur
- Insufficient knowledge on future climate variability, which is a basic element of water management
- Uncertainties in estimating changes in basin water budgets due to changes in vegetation and in atmospheric and other conditions likely to exist 50 to 100 years from now
- Uncertainties in future demands by each water sector
- Uncertainties in the socioeconomic and environmental impacts of response measures.

Hence, predicting where water resources problems due to climate change will occur can only be realized on a subcontinental scale at this time. However, water management decisions are made on the localized, watershed scale. Therefore, despite increases in the number of impact assessments and improvements in the new class of transient GCMs, there is little that can be added to the conclusions of the first two IPCC reports on the subject, other than to note the regions and countries most likely to be vulnerable through a combination of increased demands and reductions in available supplies. However, one important addition is the limited but growing analyses of water systems in the developing world. These limited studies seem to suggest that developing countries are highly vulnerable to climate change because many are located in arid and semi-arid regions and most existing water resources systems in these countries are characterized as isolated reservoir systems. Also, there is more evidence that flooding is likely to become a larger problem in many temperate regions, requiring adaptations not only to droughts and chronic water shortages but also to floods and associated damages and raising concerns about dam and levee failures (Medium Confidence).

Water management is a continuously adaptive enterprise, responding to changes in demands, hydrological information, technologies, the structure of the economy, and society's perspectives on the economy and the environment. This adaptation employs four broad interrelated approaches: new investments for capacity expansion; operation of existing systems for optimal use (instream and offstream); maintenance and rehabilitation of systems; and modifications in processes and demands (e.g., conservation, pricing, and institutions). These water management practices, which are intended to serve the present range of climate variability (which in itself is considerable), may also serve to ameliorate the range of perturbations such as droughts that are expected to accompany climate change. However, adaptations come at some social, economic, and environmental costs.

Most of the standard water resources performance criteria—such as reliability, safe yield, probable maximum flood, resilience, and robustness—are applicable in dealing with the impacts of climate change on water resources systems. This is not to suggest that we can become complacent in our response to climate change. The emphasis of water resources management in the next decades will be on responses to increased demands, largely for municipal water supply in rapidly urbanizing areas, energy production, and agricultural water supply. Water management strategies will focus on demand management, regulatory controls, legal and institutional changes, and economic instruments. The principal conclusions are as follows:

- Most of the regional water resources systems in the 21st century, particularly in developing countries, will become increasingly stressed due to higher demand to meet the needs of a growing population and economy, as well as to protect ecosystems (High Confidence).
- Arid and semi-arid watersheds and river basins are inherently the most sensitive to changes in temperature and precipitation (High Confidence).
- Water demand for irrigated agriculture is very sensitive to climate change, especially in arid and semi-arid regions (High Confidence).
- The current generation of transient GCMs, though much improved, does not offer the degree of watershed-specific information or anticipated variability in future climate required to allow robust estimates to be made regarding changes in water availability (High Confidence).
- Water demand management and institutional adaptation are the primary components for increasing the flexibility of water resources systems to meet increasing uncertainties due to climate change (High Confidence).
- Increased streamflow regulation and water management regimes may be necessary to enable water systems to meet their goals (High Confidence).
- Isolated single-reservoir systems are less adaptable to climate change than integrated multiple-reservoir systems (High Confidence).
- Technological innovations and cost-effective technologies have already played a major role in water management; likely future technological changes can serve to mitigate many of the consequences of climate change (Medium Confidence).
- Changes in the mean and variability of water supply will require a systematic reexamination of engineering design criteria, operating rules, contingency plans, and water allocation policies (Medium Confidence).
- Temporal streamflow characteristics appear to be more variable under future climate scenarios, and amplification of extremes appears likely (Low Confidence).

## 14.1. Introduction

### *14.1.1. Objectives*

Water resources are an important aspect of the world's social, economic, and ecological systems. Agriculture, hydroelectric power production, municipal and industrial water demands, water pollution control, and inland navigation are all dependent on the natural endowment of surface and groundwater resources. Civilizations have flourished and fallen as a consequence of regional climatic changes, and many "hydraulic civilizations" were formed around the need to control river flow. This endowment is not evenly distributed spatially or temporally. With the imbalance of water supply and demand, many nations are in water-scarce situations and face water crises at a local level. From 1940 to 1987, global water withdrawals increased 210%, while the world's population increased by 117% (Gleick, 1993; Shiklomanov, 1993). A global water resources assessment for the year 2025 (Strzepek *et al.*, 1995) suggests that for the United Nations median population forecast of 8.5 billion (a 55% increase over 1990) and a globally balanced economic growth path, global water use may increase by 70%.

The potential for the world to face a water-stressed condition in 2025 under population and economic growth makes assessment of possible water resource impacts associated with climate change an essential component of the IPCC assessment. Changes in hydrological processes are discussed in Chapter 10. This chapter examines the impact on water supply and use and evaluates possible water management response strategies. Water resources management is the interaction of technology, economics, and institutions for the purpose of balancing water supply with water demand and coping with hazards associated with hydrological extremes. The goal of this chapter is to provide an understanding of the sensitivity of the components of water resources systems to potential climate change. Because the water management process occurs at local and regional levels, this chapter cannot provide an assessment of global or continental impacts of climate change; however, it will glean from available literature the sensitivities of various water systems to increases and decreases in river runoff and examine changes in water demands due to changes in regional climate. Because changes in water use will affect many sectors of society and the economy, other chapters in this volume are referenced, such as those addressing wetlands, coastal zones and small islands, energy supply, transportation, human settlements, agriculture and forestry, fisheries, health problems, and financial services.

The main message of this chapter is that climate change will impact the water resources systems of the world but that we will be able to adapt—though at some cost economically, socially, and ecologically. Some analysts (Rogers, 1993a, 1993b; Klemes, 1993; Stakhiv, 1994) feel that current systems will respond well and costs will be minimal; others feel that adaptation will be difficult and in some cases extremely costly. The reason for this disparity is that the sensitivities, impacts, and costs are nonuniformly distributed across the globe. Most analyses have been conducted for regions in the developed world. The limited case studies implemented on river basins in developing countries show that sensitivities, impacts, and costs may be high. Also, much more research is needed on the response of water demands to climate change, especially non-withdrawal uses such as recreation, fisheries, wetlands, ecosystems, and waterfowl protection.

### *14.1.2. An Overview of Assessment Issues and Concepts*

The two previous IPCC assessments outlined the extensive difficulties in conducting meaningful analyses of climate-change impacts on hydrology and water resources (Shiklomanov *et al.*, 1990; Stakhiv *et al.*, 1992). Since then, many studies have been conducted in different basins—almost exclusively in developed countries—but the general conclusions of the earlier IPCC assessments have not changed. The uncertainties of climate-change impact analysis, especially at the catchment scale, remain large.

It is necessary to distinguish between the physical effects of climate change—which are reviewed in Chapter 10—and the impacts, which reflect a societal value placed on a change in some physical quantity. The impact depends largely on the characteristics of the water-use system: In some cases, a large climate-change effect may have a small impact; in others, a small change may have a large impact.

There are many different types of water supply systems in operation in the world. The simplest "system" extracts water from a local stream or village borehole; this is characteristic for most of the developing world and rural areas in many developed countries. Such supply systems, with no storage, are potentially very sensitive to climate change. The next system level consists of a single managed source—which may be a river, reservoir, or aquifer—coupled with a distribution network to provide water to users and possibly also to treat wastes and return effluents to the river. The sensitivity of such a system to climate change will depend on its characteristics—for example, on the storage-to-runoff ratio and on the seasonal distribution of water supply and demand. The most sophisticated systems are integrated networks, comprising several sources and possibly involving the transfer of water over large distances. Such systems usually are found only in developed countries; their sensitivity to climate change will depend on system structure and the degree of utilization.

Most water managers, whether they are with agencies dealing with multiple-reservoir systems or with small utilities dependent on groundwater, are concerned with three issues: new investments for capacity expansion; the operation and maintenance of existing systems; and modifications in water demand (Rogers, 1993b). Most developed countries have completed major capital-intensive developments of water resources infrastructure. Water managers in those countries operate under conditions of stable population and increased pressure for the incorporation of environmental protection objectives into the operation of existing water resources systems. The main issue they face is reallocation of existing water among competing uses. This requires continuous adaptation driven by new hydrologic information, ecological constraints, water-quality standards, and shifts in demands and preferences. Water-supply entities also may wish to explicitly or implicitly reconsider the level of service delivered. Institutional adaptation—consisting of changes in organizations, laws, regulations, and tax codes—may be the most effective means for aligning water demands with available supplies (Frederick, 1993; Rogers and Lydon, 1994; World Bank, 1994). This situation is a reality for managed water systems but less so for unmanaged systems (e.g., wetlands) dependent entirely on river flow, groundwater level, or precipitation. Water managers in developing countries are facing population growth-driven increases in water demands, and these demands are met primarily by increasing the water supply via capital-intensive investments to develop infrastructure. With planning and construction times of 20 to 30 years or more for major water projects, the question asked by many water resources managers in developing countries (Riebsame *et al*., 1995) is how climate change might impact the design of new water resource infrastructure.

***Table 14-1:*** *Summary of effects of global warming on water supply.*

| Effect of Global Warming | Impact on Water Supply Reliability |
|---|---|
| Change in river runoff | Yield in direct water abstraction<br>Yield in reservoir systems |
| Change in groundwater recharge | Yield of groundwater supply systems |
| Change in water quality | Yield of abstraction systems |
| Rise in sea level | Saline intrusion into coastal aquifers<br>Movement of salt-front up estuaries, affecting freshwater abstraction points |
| Change in evaporation | Yield of reservoir systems |

## 14.2. Impact of Climate on Water Supply

### *14.2.1. Introduction*

Climate change is likely to have an impact on both the supply of and demands for water. This section focuses on the supply of water, looking at the river catchment scale, the global and regional context, and water quality; Section 14.3 considers impacts on demands. Most climate-change impact studies have taken the form of sensitivity analyses by feeding climate-change scenarios into hydrological models. The outputs of these studies tend to be expressed in terms of changes in the reliable yield of the systems, changes in the volume of water that can be supplied, or changes in the risk of system failure. Virtually all of the studies have simulated what would happen in the absence of adaptation to change. In practice, however, water management authorities will adapt using existing or new management options—as shown to be feasible in the Great Lakes region by Chao *et al*. (1994) and Hobbs *et al*. (1995)—although such adaptation may incur added costs and involve tradeoffs that result in reductions in service for some water users. Only a few studies (Riebsame *et al*., 1995; Strzepek *et al*., 1995) have considered factors other than climate change that might affect water resources over the next few decades, such as population growth, economic development, and urbanization.

There are several possible effects of global warming on the amount of water available within a catchment or water supply area; these are summarized in Table 14-1. The relative importance of each characteristic varies considerably among catchments, depending not only on the hydrological change but also on the characteristics of the supply system. For example, a conjunctive-use system involving several reservoirs, river regulation, and groundwater boreholes will be affected differently than a supply system based on direct abstractions from an unregulated river.

Obviously, changes in river runoff will affect the yields of both direct river abstractions and reservoir-based supply systems, and changes in groundwater recharge will affect groundwater yield. Changes in water quality will affect the amount of suitable water available to a supply system. A rise in sea level has two potential effects. First, there is a risk of saline intrusion into coastal aquifers, contaminating the water supply. This is a major potential threat—particularly to small, low-lying islands, whose main source of water frequently is a shallow lens of freshwater lying just a few meters above sea level (see Chapter 9). Second, a rise in sea level would mean that saltwater could penetrate further upstream into an estuary, perhaps threatening low-lying freshwater intake works. The effects of these changes in the amount of water available on water uses—and hence on system risk and reliability—will be influenced by changes in demands.

Section 14.2.2 reviews some published studies on changes in resource availability at the catchment scale (which focus mostly on surface water resources), and Section 14.2.3 broadens the perspective to a regional scale. Section 14.2.4 reviews how changes in water quality affect the availability of water resources. The effects of changes in hydrological regimes and water quality are examined in Chapter 10.

### *14.2.2. The River Catchment Scale*

This section looks at the availability of water supplies under changed climatic conditions. For hundreds of years, people have adapted their habits and economic activities to relatively variable climatic and hydrological conditions—implicitly assuming that the average climatic state and the range of variability are stable.

This assumption may no longer be valid in some regions of the world because of possible alterations in stochastic properties of hydrological time series. Differences in the output of GCMs coupled with the variety of hydrological transfer models make it difficult to offer a reliable region-specific assessment of future water availability. It is doubtful whether the current technique of conducting "worst-case" analyses—wherein the most extreme scenario of a given GCM is used to develop hydrological responses—is useful for a critical appraisal of regional sensitivities to climate change. If anything, this type of analysis skews the evaluation and deflects the search for pragmatic responses. Progress in hydrological sensitivity analyses in developed nations is accompanied by large information gaps for developing countries that are most often affected by aridity and desertification. Although numerous new water resources impact studies have been conducted, few are from Africa, Asia, South America, or developing countries in general.

Studies that have considered possible changes in water supply in specific areas fall into three groups. The first group of studies infers changes in potential supply directly from modeled changes in annual and monthly water balance. Problems in maintaining summer supplies from direct river abstractions may be inferred, for example, if summer river flows are projected to decline (Arnell and Reynard, 1993). The second group of research has considered the sensitivity of hypothetical supply systems—usually single reservoirs—to changes in inputs. The third group of studies has largely been conducted since IPCC's 1992 Supplementary Report and consists of investigations into specific water-supply systems. Some have looked at individual reservoirs or groundwater resource systems; others have examined entire integrated water-supply systems, including real system operating rules. Table 14-2 lists these studies; several are summarized below.

These studies have simulated river flows using conceptual hydrological models but have used a variety of different scenarios. Mimikou *et al*. (1991), Wolock *et al*. (1993), Nash and Gleick (1993), and Kirshen and Fennessey (1995) all examine the effects of arbitrary changes in precipitation and temperature inputs to investigate the sensitivity of their modeled water resources systems to changes in inputs. A 20% reduction in rainfall in the Acheloos basin in Greece, for example, would increase the risk of system failure (inability to provide target supplies) from less than 1% to 38% (Mimikou *et al*., 1991); similarly, with a 20% reduction in rainfall, the New York City reservoir system in the upper Delaware valley would be in a "state of crisis" between 27% and 42% of the time, depending on temperature increases (Wolock *et al*., 1993). Nash and Gleick (1993) and Kirshen and Fennessey (1995) additionally use scenarios based on equilibrium GCM experiments, as do Gellens (1995), Kaczmarek and Kindler (1995), Riebsame *et al*. (1995), Salewicz (1995), Strzepek *et al*. (1995), and, in a generalized way, Hewett *et al*. (1993). All of these studies indicate that water resources systems could be very vulnerable to change in climatic inputs and that a small change in inputs could lead to large changes in system performance, but that there is considerable variability between scenarios. Riebsame *et al*. (1995) found isolated single-reservoir systems in arid and semi-arid regions to be extremely sensitive and less able to adapt (greater than 50% decreases in reservoir yields), with economic and ecological crisis conditions developing in some basins under climate change and seasonal flooding problems in others.

The remaining set of studies (Hobbs *et al*., 1995; Lettenmaier *et al*., 1995a, 1995b, 1995c, 1995d, 1995e; Steiner *et al*., 1995; Waterstone and Duckstein, 1995; Shiklomanov *et al*., 1995), largely undertaken in the United States, have used scenarios based on the three most recent transient GCM simulations (GFDL-tr, UKMO-tr, and MPI-tr) to investigate possible impacts on integrated, multipurpose water resources systems. All of these studies note the difficulties in forecasting meaningful impacts under the wide range of uncertainties inherent in the analysis; in many cases, the GCM simulations did not reproduce current catchment climate very well. However, a general conclusion from the studies is that even with the large variability in future climate represented by the three transient GCM experiments, most of the systems investigated possess the robustness and resilience to withstand those changes, and adequate institutional capacity exists to adapt to changes in growth, demands, and climate. This conclusion is in contrast to that of many other studies—some summarized above—that have found large changes in system reliability under climate change. There are two main reasons for this difference: First,

***Table 14-2:*** *Investigations into effects of global warming on specific water resources systems.*

| Location | Reference |
|---|---|
| Africa: Nile River | Strzepek *et al*. (1995) |
| Africa: Zambezi | Riebsame *et al*.(1995) |
| Africa: Zambezi River | Salewicz (1995) |
| Asia: Ganges and Brahmaputra | Kwadijk *et al*. (1995) |
| Asia: Indus River | Riebsame *et al*. (1995) |
| Asia: Mekong River | Riebsame *et al*. (1995) |
| Belgium | Gellens (1995) |
| England (southeast) | Hewett *et al*. (1993) |
| Greece | Mimikou *et al*. (1991) |
| Poland | Kaczmarek and Kindler (1995) |
| Russia and Ukraine: Dnipro River | Shiklomanov *et al*. (1995) |
| Uruguay | Riebsame *et al*. (1995) |
| USA: Boston area (1) | Kirshen and Fennessey (1995) |
| USA: Boston area (2) | Lettenmaier *et al*. (1995b) |
| USA: Colorado River | Nash and Gleick (1993) |
| USA: Columbia River | Lettenmaier *et al*. (1995c) |
| USA: Delaware River | Wolock *et al*. (1993) |
| USA: Great Lakes | Hobbs *et al*. (1995) |
| USA: Missouri River | Lettenmaier *et al*. (1995d) |
| USA: Potomac River | Steiner *et al*. (1995) |
| USA: Rio Grande River | Waterstone and Duckstein (1995) |
| USA: Savannah River | Lettenmaier *et al*. (1995a) |
| USA: Tacoma area | Lettenmaier *et al*. (1995c) |

the transient scenarios tend to produce smaller changes in climate than the scenarios based on earlier GCMs; second, the transient-GCM studies examine highly integrated systems, which are inherently more robust than the isolated single-reservoir systems investigated in most other studies.

In some countries, water is predominantly taken from rivers, lakes, and reservoirs; in others, it largely comes from aquifers: Only 15% of Norwegian water is taken from aquifers, for example, whereas 94% of Portuguese supplies comes from groundwater. There have been very few studies of changes in groundwater recharge and implications for aquifer yield. Hewett *et al.* (1993) simulate an increase in recharge, and hence an increase in reliable yield, in part of the chalk limestone aquifer in southern England, but different scenarios in the same region suggest a decline in yield. The effect of a sea-level rise on saline intrusion into coastal aquifers has been investigated in a number of small islands and has been found to be potentially significant (see Chapter 9). Studies in Britain, however, have found that although there are many coastal aquifers potentially at risk, a rise in sea level would have little effect on intrusion and yields (Clark *et al.*, 1992). Saline intrusion along estuaries generally has been found to pose limited threats to freshwater intakes because the change in the position of the salt front is small relative to the intertidal range (Wolock *et al.*, 1993; Dearnaley and Waller, 1993).

This section has introduced some of the studies into water resource availability that have been undertaken in the last five years. There are several points to draw in conclusion. First, there are considerable uncertainties in estimating impacts, due partly to uncertainties in climate-change scenarios and partly to difficulties in estimating the effects of adaptations—both autonomous and climate-induced—over the next few decades. Second, there is evidence that isolated, single-source systems are more sensitive to change than integrated, multipurpose systems, which are considerably more robust. Much of the world's water, however, is managed through single-source, single-purpose systems. Third, there is a suggestion that, in countries with well-managed, integrated water resources, the additional pressures introduced by climate change could be met, with some costs, by techniques already in place to cope with changing demands and management objectives. There is little information, however, about the economic and societal costs of this adaptation. Waterstone *et al.* (1995), for example, conclude that institutional adaptation—changes in water laws, organizations, prices, fees, water marketing, and reservoir operating criteria—could serve to ameliorate the combined effects of increasing population and warming in the semi-arid Rio Grande basin in the southwestern United States, and Hobbs *et al.* (1995) believe that conventional management practices for coping with fluctuating lake levels would be capable of mitigating the effects of climate change on the Great Lakes. Fourth, and perhaps most important, some studies (Riebsame *et al.*, 1995; Strzepek *et al.*, 1995) show that water resources in developing countries often are small-scale, isolated, and under considerable stress and may have a difficult time adapting to climate change effectively. Although the latter studies cover a range of hydroclimatic zones, there is still a major gap in our understanding of the impacts of climate change on the less-developed world—a situation that urgently needs to be rectified. The U.S. Country Studies Program currently is cooperatively studying the vulnerability and adaptability of water resources systems in more than 30 developing countries, with results expected in 1996.

### *14.2.3. The Global and Regional Context*

The growing interest in possible consequences of anthropogenic climate change on regional water resources has given rise to a wealth of studies on the sensitivity of water balance to climatic variables. Much less information is available on the economic and societal consequences of projected global warming. The heaviest current pressures on water resources are the increasing population in some parts of the world and increasing concentrations in urban areas. The illusion of abundance of water on the Earth has clouded the reality that in many countries renewable freshwater is an increasingly scarce commodity (Postel, 1992; World Bank, 1992, 1994; Engelman and LeRoy, 1993). Climate change is likely to have the greatest impact in countries with a high ratio of relative use to available renewable supply. Regions with abundant water supplies are unlikely to be significantly affected, except for the possibility of increased flooding. Paradoxically, countries that currently have little water—for example, those that rely on desalination—may be relatively unaffected.

One study (Strzepek *et al.*, 1995) suggests that, although global water conditions may worsen by 2025 due to population pressure, climate change could have a net positive impact on global water resources. This result, presented in Figure 14-1, is based on runoff characteristics obtained for one particular climate scenario (Miller and Russel, 1992) and should be interpreted with caution. Another macroscale study (Kaczmarek *et al.*, 1995)—based on three transient climate scenarios—leads to a similar conclusion for the Asian continent, while suggesting that in Europe changed climatic conditions will be associated with some decrease of per capita water availability.

Following the concept of Falkenmark and Widstrand (1992) of a water stress index based on an approximate minimum level of water required per capita, Engelman and LeRoy (1993) use 1,000 $m^3$ per person per year as a benchmark for water scarcity around the world. They found that in 1990 about 20 countries, with a total population of 335 million, experienced serious chronic water problems and that by 2025, 31 countries with 900 million inhabitants could fall into this category because of expected population growth. Table 14-3 summarizes the combined impact of population growth and climate change on water availability in selected countries, based on the IPCC (1992a) socioeconomic scenarios and the results of three transient GCM runs. The second column lists per capita water availability for the present (1990); the third column shows water availability for current climatic conditions, reflecting population growth alone to the year 2050. The last column shows the range of

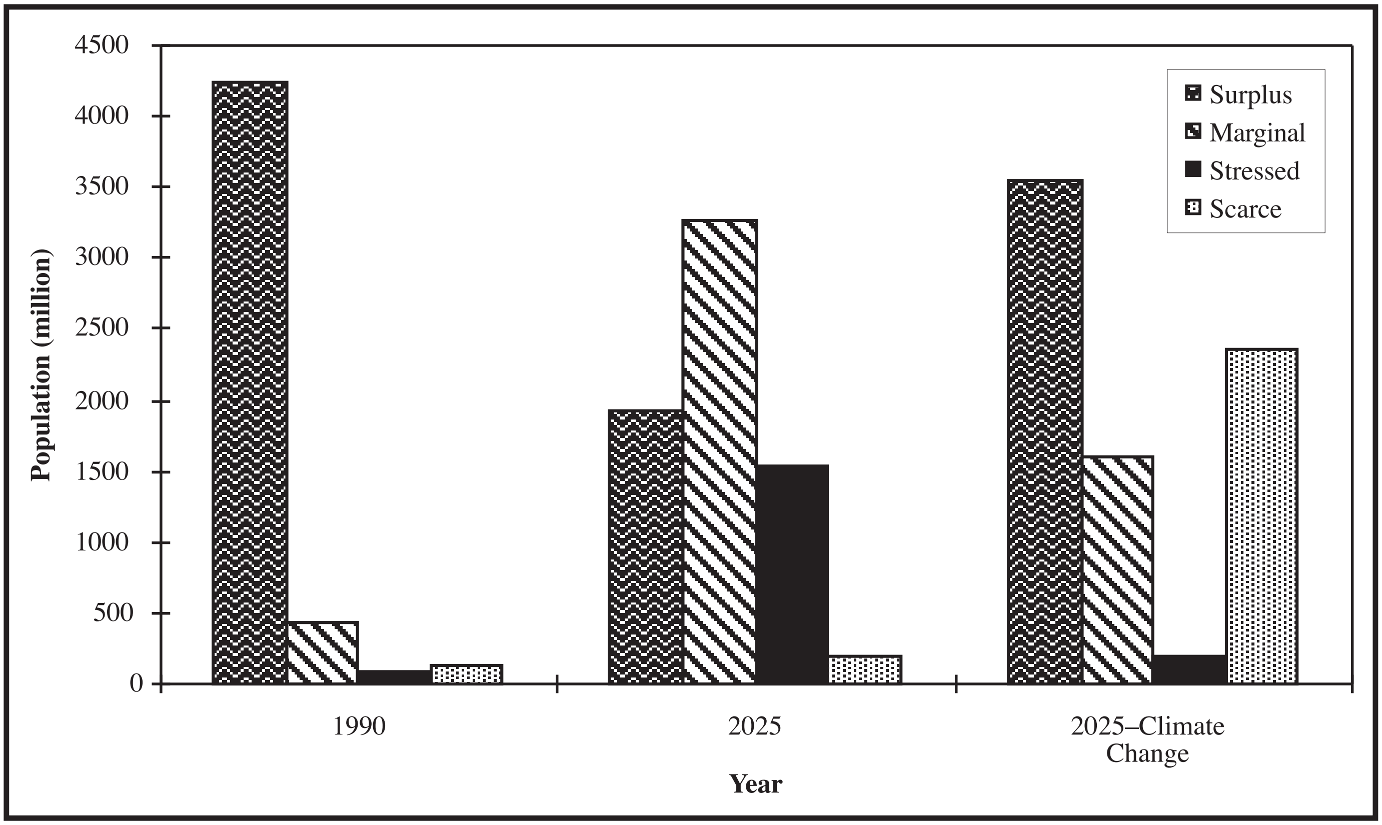


**Figure 14-1:** Global freshwater vulnerability (Strzepek *et al*., 1995).

combined effects of population growth and climate change for the three transient scenarios. The sensitivities of national water supplies to changes in temperature and precipitation were estimated by a method proposed by Kaczmarek (1990). It should be added that the future water availability data do not take into account possible changes in water resources systems development (e.g., increased storage, desalination).

The results show that in all countries with high population-growth rates, future per capita water availability will decrease independent of the assumed climate scenario. Large discrepancies may be noted among results obtained for some countries by means of various atmospheric models. This example clearly demonstrates how difficult it would be to initiate water resources adaptation actions based on currently available methods of climate predictions. It can be expected that in many regions of the world, nonclimatic factors will dictate what measures must be undertaken to secure sustainable water supply (Frederick, 1994; Rogers and Lydon, 1994). Predicted climate changes, however, could redistribute water supplies, adding a new, highly uncertain component to the challenge of managing water resources.

Although it is appealing to devise thresholds or benchmarks for water scarcity, such as the one proposed by Falkenmark and Widstrand (1992)—in which economic water scarcity is defined as the condition in which renewable freshwater availability falls below 1,000 $m^3$ per person per year—it is important to realize that such a threshold is useful only as a rough benchmark for comparison of relative conditions, perhaps to serve as a cautionary flag. Other comparable thresholds have been suggested at 1,700 $m^3$ per person per year to reflect a condition of water stress, whereas the World Bank (Falkenburg *et al*., 1990) suggests a 500 $m^3$ per person per year threshold. On the other hand, Rogers (1992) considers such thresholds not useful in developing water management strategies, noting that both Malta and Israel—with annual per capita water availabilities of 85 $m^3$ and 460 $m^3$, respectively—are doing quite well in managing, recycling, and reclaiming their very limited water supplies.

Water availability, food production, population and economic growth, and climate change are linked in a complex way. Conflicts among interests are inherent in regional water management, particularly in regions with scarce water resources. Four objectives important for sustainable water planning may be identified: economic efficiency, environmental quality, equity considerations, and reliability. Transformation in the structure and characteristics of water supply and demand due to climatic and nonclimatic factors may add new aspects to existing social and political problems. Socioeconomic factors greatly influence the ability to solve these problems in the absence of necessary institutions, capital, and technology.

Access to freshwater may be complicated by conflicts arising over rights to water in shared river basins (e.g., Mekong and Nile—Riebsame *et al*., 1995) and in aquifers that cross international borders (Engelman and LeRoy, 1993). A great number

*Table 14-3: Water availability (m³/yr) in 2050 for the present climatic conditions and for three transient climate scenarios (GFDL, UKMO, MPI).*

| Country | Present Climate (1990) | Present Climate (2050) | Scenario Range (2050) |
|---|---|---|---|
| China | 2,500 | 1,630 | 1,550–1,780 |
| Cyprus | 1,280 | 820 | 620–850 |
| France | 4,110 | 3,620 | 2,510–2,970 |
| Haiti | 1,700 | 650 | 280–840 |
| India | 1,930 | 1,050 | 1,060–1,420 |
| Japan | 3,210 | 3,060 | 2,940–3,470 |
| Kenya | 640 | 170 | 210–250 |
| Madagascar | 3,330 | 710 | 480–730 |
| Mexico | 4,270 | 2,100 | 1,740–2,010 |
| Peru | 1,860 | 880 | 690–1,020 |
| Poland | 1,470 | 1,250 | 980–1,860 |
| Saudi Arabia | 310 | 80 | 30–140 |
| South Africa | 1,320 | 540 | 150–500 |
| Spain | 3,310 | 3,090 | 1,820–2,200 |
| Sri Lanka | 2,500 | 1,520 | 1,440–4,900 |
| Thailand | 3,380 | 2,220 | 590–3,070 |
| Togo | 3,400 | 900 | 550–880 |
| Turkey | 3,070 | 1,240 | 700–1,910 |
| Ukraine | 4,050 | 3,480 | 2,830–3,990 |
| United Kingdom | 2,650 | 2,430 | 2,190–2,520 |
| Vietnam | 6,880 | 2,970 | 2,680–3,140 |

of water resources systems are shared by two or more nations. In several cases, there have already been international conflicts. As a result of population pressure, and in cases of negative impacts of climate change, tensions are likely to increase. In order to avoid future conflicts over water use among riparian countries, joint legal agreements should be established. One possibility is to form international water agencies or commissions, with terms of reference including inventory, assessment, monitoring, and apportionment of water resources and due account for possible changes caused by climatic trends. Joint planning is essential for basin-scale water resources development and management in order to cope with negative consequences of climate change. International water agencies should arbitrate on regional water issues and be supported by national legal frameworks to back the regional arbitration accordingly. To be able to fulfill this task, international water agencies in developing countries require well-trained people with knowledge of global-scale processes and, in some cases, external funding for research and development.

### *14.2.4. Implications of Changes in Water Quality*

Water management is concerned not merely with the supply of water but with the supply of water of appropriate quality as well. The definition of "appropriate" varies among uses. Potable water has to be of the highest quality, whereas industry and, to a lesser extent, agriculture can use lower-quality water. Irrigation increasingly employs recycled "dirty" water, raising concern about salinity and public acceptance of wastewater use. Many water management problems around the world today, in fact, relate to the quality of surface water and groundwater. Climate change might exacerbate some of these problems by complicating an already expensive, evolving management process. Water-quality problems usually stem from some form of pollution, ranging from the discharge of untreated sewage into watercourses to the discharge of treated sewage effluent, the leaching of agricultural chemicals, and chemical and thermal pollution from industry. There is a considerable range of experience in dealing with water quality. In some countries, the focus is on preventing poor water quality; in others, effort is directed toward rehabilitation, treatment, sanitation, and public health. In many countries, water quality is hardly addressed at all.

The potential effects of climate change on aquatic ecosystems are reviewed in Chapter 10. Of particular concern for water users are dissolved oxygen content, nitrate and organic pollution concentrations, sediment load, and salinity. The main conclusion is that rivers that presently have poor water quality are likely to be those most affected by changes in temperature, lower flow rates, and increased input of pollutants; climate change is therefore likely to exacerbate water-quality problems in places where such problems already are potentially severe.

Water management agencies in many countries are spending significant sums on maintaining and improving surface and groundwater quality. Although approaches vary, improvement plans tend to include target water-quality and effluent standards, infrastructure for treating effluent returns and polluted water, policies to prevent pollution, and policing. These actions also can be used to maintain and improve water quality under climate change, obviously at some additional cost. For example, it may be necessary to reduce the quantity of treated effluent that can be discharged to a stream with reduced flows, with consequent implications for the discharging organization.

## 14.3. Impact of Climate on Water Demands

Section 14.2 considered changes in the ability of water resources systems to supply water; this section looks at the demand side. It is useful to distinguish between offstream demands—specifically domestic, industrial, and agricultural demands—and instream demands, such as power generation, navigation, recreation, and ecosystems protection. Increases in water demand are driven by population and economic growth. Demand management has two dimensions: the first long-term, the second in response to short-term shortages. In the long term, one can reduce offstream water demands substantially through technological, economic, legal and administrative, and educational measures. In the short term, demand during temporary supply shortages can be managed through demand reduction measures (such as rationing) and public education.

### *14.3.1. Agricultural Water Demands*

At present, more than 65% of global water withdrawals is for agricultural use; much of this is evaporated and consequently lost to catchment runoff. Irrigation increased significantly until the 1970s, when the rate of expansion fell sharply; since 1980, the annual rate of expansion has been less than 1%—less than the rate of population increase (Postel, 1992). Rapid expansion in the future is unlikely as the cost of developing new schemes increases and investments in irrigation decline. Agricultural irrigation practices are inefficient in many areas of the world. Changes in irrigation technology (such as the use of drop irrigation) often can compensate for anticipated increases in food demands. The effects of climate change on agricultural policy and irrigation requirements are discussed in Chapter 13. It is important to emphasize that the effects of climate change on agricultural demands for water, particularly for irrigation, will depend significantly on changes in agricultural potential, prices of agricultural produce, and water costs.

Both rainfed and irrigated crops will require more water in a warmer world, and this water may not be available through increased precipitation. Allen *et al*. (1991) simulate changes in irrigation demand in the Great Plains region of the United States, showing that the demand for water to irrigate alfalfa would increase, due largely to increases in the length of the crop growing season and crop-water requirements during summer. Another U.S. study—based on a Thornthwaite water-balance model (McCabe and Wolock, 1992)—indicates that, for a broad range of increases in temperature and precipitation, annual irrigation demand increases, even with a 20% increase in precipitation. In a study in Lesotho, Arnell and Piper (1995) simulate an increase in irrigation demands of 7% with a 10% decline in runoff and an increase of more than 20% with a 2°C increase in temperature. They also examine the performance of a hypothetical reservoir supplying irrigation water and find major changes in the reliability of supply. Studies in the UK lead to the conclusion that an increase in temperature of 1.1°C by 2050 may result in an increase in spray irrigation demands of 28%, over and above a projected 75% increase to meet growing demands (Herrington, 1995). Similar calculations in Poland result in a 12% increase in irrigation demands with a 1°C temperature increase and a 1.8% change in water requirements with a 1% precipitation change during the vegetation season. Irrigation demand seems to be more sensitive to changes in temperature than to changes in precipitation. Model results indicate that increased stomatal resistance to transpiration counteracts the effects of temperature increases on irrigation demand.

### *14.3.2. Municipal Demands*

Municipal demands are essentially for domestic and commercial uses. In many developed countries, some components of demand are decreasing due to greater appliance efficiency, but others are increasing as new appliances, such as waste disposal units and automatic washing machines, become more widespread. Herrington (1995) estimates changes in the components of domestic demand in southern England, with and without climatic change and assuming no change in water pricing policies. An increase in per capita demand of 21% is projected between 1991 and 2021 without climate change, with an additional 5% increase due to global warming—largely due to an increase in garden water use. Other studies have found a similar percentage change in domestic and municipal demand due to global warming (Cohen, 1987; Kaczmarek and Kindler, 1989; Kirshen and Fennessey, 1993; Hanaki, 1993; Steiner *et al*., 1995). Little is known about the impact of climate change on domestic water use in developing countries, but nonclimatic factors—population growth, economic development, water-use efficiency, and water pricing—probably will dominate in shaping trends of future water use in most African and Asian regions.

### *14.3.3. Industrial Water Use and Thermal and Hydropower Generation*

In most developed countries, the demand for water for industrial purposes is declining as traditional major water users such as the steel industry decline in significance and as water is used more efficiently. It should be added, however, that in many cases these water-consuming industrial users are relocating to the developing world, complicating the water resource situation in those regions. Strzepek and Bowling (1995) have found that under a moderate growth assumption, global industrial water use in 2025 may increase by 1.7 to 2.3 times 1990 levels, and most of this growth will occur in the developing world. Climate change is expected to have little direct impact on industrial water use.

A change in water quantity may affect the degree to which demands for cooling water can be satisfied, and a rise in water temperature will reduce the efficiency of cooling systems (Dobrowolski *et al*., 1995). It also might be more difficult to meet regulatory constraints defining acceptable downstream water temperatures, particularly during extreme warm periods. Several French nuclear power stations were forced to close down or operate well below design capacity during the drought of 1991. A reduction in water availability might lead to an increase in the use of closed-cycle cooling systems as simulated in the Tennessee Valley Authority system (Miller *et al.*, 1993). Changes in water availability and temperature may not cause significant impacts on long-term or annual total production potential—only a 2% decline in annual net system generation was found in the Tennessee Valley—but they could cause short-term operational problems during critical periods.

A change in hydrological regimes has an obvious potential impact on hydropower production but also may affect thermal power generation and general industrial demands for cooling water. Mimikou *et al*. (1991) show a very large change in the risk of being unable to generate design power from hydropower reservoirs in central Greece. In Norway, Saelthun *et al*. (1990) find increased generation potential due largely to a shift in the timing of inflows, mainly as a result of reduced snowfall; the current "waste" of power in the spring is much reduced.

Riebsame *et al*. (1995) examine hydropower generation in four developing-country basins. In the Zambezi basin, the possible reduction of hydropower at Lake Kariba could be replaced by the construction of a new plant at Batoka Gorge, but for a significant cost. Hanemann and McCann (1993) examine the economic cost of changes in hydropower potential in northern California. Under a scenario based on the GFDL equilibrium GCM, annual hydropower production would decrease by 3.8%; production would be 48% higher in January but as much as 20% lower during the peak-load summer months. Water would have to be released during the spring to leave room for flood control. As a result of the reduced hydropower generation, production of power by natural gas would have to increase by 11% to meet the same demands, leading to a $145 million (1993 prices) increase in annual system costs (12.5%). In some cases, the expected shift in the runoff hydrograph, combined with changes in the distribution of irrigation water demands, may lead to reduced energy generation.

### *14.3.4. Navigation*

Changes in flow regimes and lake levels can be expected to affect navigation potential, but there have been very few studies on this topic. The sensitivity of river navigation to extreme conditions was well illustrated on the Mississippi River during the drought of 1988, when river traffic was severely restricted (with consequent effects on the agricultural sector due to difficulties in transporting the grain harvest). High river flows also restrict navigation by increasing energy costs and flooding riverside facilities. Navigation on the river Rhein, for example, is constrained by periods of both high and low flows, and considerable sums are spent on dredging and maintaining channels; a change in sediment load could have major implications for these activities. An increase in temperature, however, would increase the duration of the navigation season on rivers affected by seasonal ice cover. Studies in the Great Lakes (Chao *et al*., 1994) suggest that a longer shipping season due to a reduction in ice cover would just compensate for lost draft due to lower levels; shipping companies would be able to adjust their operating season in the Great Lakes because many of the raw materials transported are stockpiled.

### *14.3.5. Recreation and Other Instream Water Uses*

There have been very large investments in water-based recreation in many countries, and many large facilities are operated to maximize recreation potential. The effects of global warming on recreation are difficult to determine. Changes in the volume of water stored in a reservoir might affect the use of the reservoir for recreation (Frederick, 1993), and a change in water quality might also affect the recreational use of the water. There are established procedures for estimating the economic benefits of access to recreation, but the sensitivity of recreational use to hydrological characteristics—reservoir storage volume, water quality, and so forth—is not well known; the effects of possible changes therefore are difficult to quantify. One exception is the Great Lakes, where there are clear relationships between beach area, length of recreation season, and recreational benefits: Both beach area and recreation season length would increase under climate warming, resulting in an estimated doubling of recreational benefits, according to Chao *et al*. (1994).

One-tenth of the world's commercial fish yield is obtained from inland waters (Covich, 1993), and recreational fishing also has high economic value. The effects of changes in water temperature, water quality, and river flow regimes on fish populations are outlined in Chapter 10; this section focuses on implications of changes for sport fishing and aquaculture. Hanemann and Dumas (1993) simulate the effects of one global warming scenario on Chinook salmon runs in the Sacramento River, California, and find a reduction in the salmon population largely due to reductions in spawning habitats. Loomis and Ise (1993) estimate the change in the economic value of recreational fishing in the Sacramento River based on an empirical relationship between the number of fish caught and the number of fishing trips made. The reductions in fish population result in an annual loss of recreational benefit of $35 million (1993 values)—a 23% decrease (assuming no change in anglers' willingness to travel to the river).

Stefan *et al*. (1993) conclude that, for the state of Minnesota, the impact of climate change on fishery resources may be significant. Overall fish production may increase, but cold-water fisheries will be replaced in part by warm-water fisheries. This coincides with findings in Poland and Hungary related to the impact of thermal pollution. The comprehensive study of fish yields performed by Minns and Moore (1992) in several hundred watersheds in eastern Canada shows considerable redistribution of fishery capability.

The final instream use to be considered in this section is ecosystem protection. Instream ecosystems demand a certain minimum quantity of water (which may vary throughout the year), and water managers in many countries increasingly are balancing these demands with those of more traditional water users. Several techniques are being developed to estimate instream demands (Stalnaker, 1993); these techniques can be used in principle to estimate the effects on these demands of changes in water availability. However, this has not yet been done, largely because the instream demand models are very uncertain. In principle, it might be possible to maintain certain aquatic ecosystems by managing river flow regimes to minimize changes, but this is perhaps not desirable in an ecological sense because it would create a system that would not be sustainable without human intervention. The general issue of managing the impacts of climate change on natural ecosystems is discussed in Chapter 10 and elsewhere.

### *14.3.6. Competition Between Demands*

Water demand in general increases in all sectors with an increase in temperature; this is a well-accepted consequence of climate change. At the same time, regional and local precipitation changes, which will have important impacts on water demands, are much less clear. Studies of individual sectors and systems show great potential for adapting to water conditions in a changed climate. However, as we move into the 21st century, population and economic pressures may create water-stressed conditions in many parts of the world. Many of the responses being proposed to adapt to climate change require reduction of demands and reallocation of water among water-use sectors.

Present water management is concerned with reconciling competing demands for limited water resources. Currently, these conflicts are solved through legislation, prices, customs, or a system of priority water rights. Change in the amount of water available and water demands is likely to lead in many cases to increased competition for resources. Conflicts may arise between users, regions, and countries, and the resolution of such conflicts will depend on political and institutional arrangements in force. The challenge will be to create integrated demand/supply management systems, as discussed below.

## 14.4. Management Implications and Adaptation Options

### *14.4.1. Considerations for Response Strategies*

In general, most countries and civilizations have faced water shortages due to natural climate variability, anthropogenic changes and desertification, or overexploitation and pollution of the resource base. Management of water resources inherently entails mitigating the effects of hydrological extremes and providing a greater degree of reliability in the delivery of water-related services. Because different uses have different priorities and risk tolerances, the balance points among them after climate change could be quite different from the present (e.g., hydropower and instream uses may be lost disproportionately compared to water supply). No enterprise is risk-free: Society decides on the level of risk-bearing through the acceptance of certain levels of risk and reliability, as expressed by cost-effective standards and criteria. The marginal cost of reducing each additional increment of risk typically rises rapidly as reliability approaches 100%. Hence, water managers usually deal with 90%, 95%, and 99% levels of reliability as useful performance measures of the available quality and quantity of water.

The same is true in mitigating other natural hazards, especially in traditional approaches to drought mitigation, flood control, and damage mitigation. Given some of the preliminary results of GCM experiments regarding potential changes in rainfall intensity and frequency (Gordon *et al*., 1992; Whetton *et al*., 1993), it appears that flood-related consequences of climate change may be as serious and widely distributed as the adverse impacts of droughts. This should raise concerns about dam safety and levee design criteria and spur reconsideration of flood plain management policies. The devastating floods of 1993 in the upper Mississippi River basin have resulted in a U.S. Interagency Floodplain Management Review Committee report (1994) on just such policy issues, exemplifying the need for constant adaptation in the field of water resources management. Comparable adaptations are anticipated in the wake of the most recent European floods of January 1995.

To alleviate human-induced droughts occurring at a regional scale as a consequence of inappropriate land-use practices, wise criteria for land use should be developed to minimize storm-induced runoff and, consequently, minimize erosion and nutrient loss and maximize interception and infiltration. Such strategies would maintain or enhance the recycling of moisture, which at a (sub)continental scale is necessary to sustain rainfall in the region. Most watershed management practices for erosion control and water harvesting do contribute, albeit unintentionally, to the reestablishment of moisture feedback to the atmosphere and, consequently, to the recycling of moisture and rainfall. In view of the vulnerability of regions presently affected by anthropogenic droughts and the dire consequences of resulting desertification, this field of research merits full attention.

The first IPCC reports (1990a, 1990b) contain a discussion of the philosophy of adaptation and a list of adaptation options suited to the range of water management problems that are expected under climate change. Based on a review of the most recent literature, no additional water management actions or strategies unique to climate change have been proposed as additions to the list, other than to note that many nations have pledged to implement action plans for sustainable water resources management as part of their obligation toward Agenda 21. In that respect, the principles laid out in that document would serve as a useful guide for developing a strategy that would enable nations, river basin authorities, and water utilities to prepare for and partially accommodate the uncertain hydrologic effects that might accompany global warming. The World Bank (1993) lays out a framework for water resources management that is expected to serve the needs of developing nations well into the next century and to meet the objectives of Agenda 21.

There are many possibilities for individual adaptation measures or actions. An overview of water supply and demand management options is presented by Frederick (1994) as part of an attempt to develop approaches for dealing with increasing water scarcity. A long-term strategy requires the formulation of a series of plausible development scenarios based on different combinations of population growth assumptions along with economic, social, and environmental objectives (Carter *et al*., 1994). After these scenarios are established, taking into account the possibility of climate change, a set of alternative long-term strategies for water management must be formulated that consists of different combinations of water management measures, policy instruments, or institutional changes, and is designed to best meet the objectives of a particular growth and development scenario and its consequent $CO_2$ emissions rate. The range of response strategies must be compared and appraised, each with different levels of service reliability, costs, and environmental and socioeconomic impacts. Some will be better suited to dealing with climate change uncertainty (i.e., more robust and resilient), and others will focus on environmental sustainability. Some are likely to emphasize reliability of supply. The reality is that, after the application of engineering design criteria to various alternatives, the selection of an "optimal" path is a decision based on social preferences and political realities. Engineering design criteria, however, also evolve over time and are updated as new meteorological and hydrological records are extended and the performance of water management systems is tested under varying conditions.

All major institutions that deal with water resources planning and management agree that future water management strategies should include various cost-effective combinations of the following management measures:

- Direct measures to control water use and land use (regulatory, technological)
- Indirect measures that affect behavior (incentives, taxes)
- Institutional changes for improved management of resources
- Improvement in the operation of water management systems
- Direct measures that increase the availability of supply (reservoirs, pipelines)
- Measures that improve technology and the efficiency of water use.

Different strategies apply to different circumstances. Watersheds that have little or no control over natural flows and are largely dependent on precipitation must implement a different set of water management strategies than river basins with a high degree of control in the form of reservoirs, canals, levees, and so forth. Similarly, rapidly urbanizing areas will require different responses than agricultural regions. There is no standard prescribed approach. However, a rational management strategy undertaken to deal with the reasonably foreseeable needs of a region in the absence of climate change, according to the principles espoused in Agenda 21, also will serve to offset many of the possible adverse consequences of climate change.

### *14.4.2. Implications for Planning and Design*

The nature of contemporary water resources management is such that countless numbers of principal factors, economic criteria, and design standards are incorporated simply because of the complexity of integrated water management (e.g., hydropower, ecosystem support, water supply) and objectives (e.g., reliability, costs, safety). Some factors that are routinely assessed inherently represent design thresholds such as the minimum instream flow required for maintaining an aquatic ecosystem or the "probable maximum flood" that is used for most dam-safety risk analyses. The accepted level of water supply reliability of a system is a threshold as well, determined essentially by public preference, economics, and engineering analysis. Planning, by its nature, has inherent risks and develops alternative plans that are packages of complementary actions, project regulations, and management measures that reduce risks in different water-use sectors (with a variety of socioeconomic and environmental impacts and a range of benefits and costs).

Engineering design is largely concerned with performance and reliability. Once a particular plan is selected, engineers ensure that each of the separate components functions as planned and that, collectively, the water management system performs reliably. This was true in Roman times (Frontinus, 98 AD) as well as in contemporary times. Water resources systems are designed to perform reliably over most but not all of the range of anticipated hydrological variability. That reliability criterion is determined through a combination of risk, costs, benefits, environmental impacts, and societal preference. Hence, if climate change alters the frequency, duration, and intensity of droughts and floods, new reliability criteria will evolve over time to adjust for the perceived changes in both availability and use—as will the corresponding types of adaptive behavior.

It also is useful to think of hydrological or watershed response sensitivity to change measured in terms of physical effects. A complementary notion is the susceptibility of various water-use sectors (e.g., hydropower, irrigation, recreation) to incremental changes of outputs (e.g., kilowatt-hours, revenues, visitors). Finally, the vulnerability to failure of a water management system itself—consisting of pipes, pumping stations, reservoirs, and delivery rates—also must be appraised in terms of reliability targets measured as changes in quality, quantity, and probability. To that end, water resources planners, hydrologists, and design engineers have developed a set of practices that explicitly address a range of hydrological, economic, and engineering risk and uncertainty factors and implicitly encompass some notion of sensitivities and thresholds. Fiering (1982) and Hashimoto *et al*. (1982a, 1982b) developed the concepts of robustness (sensitivity of design parameters and economic costs to variability); reliability (a measure of how often a system is likely to fail); resiliency (how quickly a system recovers from failure); vulnerability (the severity of the consequences of failure); and brittleness (the capacity of "optimal" solutions to accommodate an uncertain future). Many if not most of these concepts are analyzed as part of contemporary hydrological and water resources management decisions (Kundzewicz and Somlyody, 1993; Kaczmarek *et al*., 1995). Riebsame *et al*. (1995) analyze the sensitivities and adaptabilities of five international river basins in the context of the criteria discussed above. The results are presented in Table 14-4.

***Table 14-4:*** *Overall basin sensitivity and adaptability (Riebsame et al., 1995).*

| Basin | Hydrological Sensitivity | Structural Robustness | Structural Resiliency | Adaptive Capacity |
|---|---|---|---|---|
| Uruguay | moderate | high | high | high |
| Mekong | low | low | high | low |
| Indus | moderate | high | moderate | high |
| Zambezi | high | low | low | low |
| Nile | high | high | low | low |

There is a growing tendency to devise management systems that complement supply development with demand management. Nonstructural management measures are increasingly relied on to provide needed robustness without decreasing the overall reliability of a system. Hence, flood-control levees in the United States are now designed to provide varying levels of protection, whereas in the past there was a fixed level of flood protection based on a calculation of the "standard project flood." Today, a levee can be designed to offer protection against a flood with a 2% chance of occurrence (a 50-year return period) in conjunction with a well-organized flood warning and evacuation plan. For example, all 360 U.S. Corps of Engineers reservoirs have both drought contingency plans and flood warning and dam-safety evacuation plans. However, it is important to remember that the combination of numerous design factors, operating rules, reservoir storage allocation decisions, flood forecasting and evacuation planning, and drought contingency planning provides a considerable degree of robustness, resiliency, and flexibility to contend with uncertainty and surprises. Coupled with demand management and institutional and regulatory changes that are needed to cope with anticipated changes in population and demands, water management systems of this scale, if properly managed, offer a well-balanced strategy for dealing with risk and uncertainty, including many of the impacts of climate change. The purpose is to reduce, if not minimize, the adverse social, economic, and environmental consequences of changes in water resources regardless of the agent of change (Stakhiv, 1994), although the costs of adaptation to climate change could be substantial. Most important is the reality that water resources management is an inherently continuous adaptive endeavor at many different levels and spatial scales.

This is not to suggest that we can become complacent in our response to climate change. The challenges and barriers to implementing the water management principles of Agenda 21 are difficult enough to overcome. The water situation in the Middle East and North Africa is precarious and projected to deteriorate as a consequence of population growth and unplanned development. In sub-Saharan Africa (World Bank, 1994), the water situation is expected to worsen due to desert encroachment and drying up of water sources as a result of increased deforestation. Droughts, desertification, and water shortages are a permanent feature of daily life in those countries. The list of nations with water supply problems will expand with the accelerated pace of urbanization. By the year 2030, urban populations will be twice the size of rural populations. By 2000, there will be 21 cities in the world with more than 10 million inhabitants, 17 of which will be in developing countries. It is expected that the population without safe drinking water will increase from 1 billion people in 1990 to 2.4 billion by 2030, assuming a "business-as-usual" scenario. Similarly, population without adequate sanitation will grow from 1.7 billion to 3.2 billion by the year 2030 (World Bank, 1992). Addressing these issues would make it easier to cope with the impacts of climate change when and if they become significant (IPCC, 1992; Goklany, 1992).

On the other hand, the picture may not be as bleak as it appears, in the sense that it is easier and more efficient to organize a water supply, treatment, and delivery system for urban areas with concentrated populations. Also, demands can be more easily managed to promote water-use efficiency. Although municipal and industrial water use will grow, per capita use is likely to decrease and the quality of drinking water will increase with centralized treatment. Many future urban water demands are likely to compete with the irrigated agricultural sector—which uses about 88% of all water withdrawn in Africa, 86% of all water withdrawn in Asia, and 87% of all water withdrawn in the arid Middle East and North Africa (World Bank, 1994). New sources of supply will have to be developed, but existing water use will have to be more effectively managed and efficiently used.

The reality is that increasing water demands will intensify competition for scarce water and further concentrate water use in urban centers. During the next 30 years, these real and complex needs will preoccupy water managers. Water management planning will address these needs, which precede the climate-change signal and thereby serve as a *de facto* adaptation mechanism. Climate change, in its many manifestations, is likely to be a perturbation on what are already difficult and complicated water management problems. Existing drainage systems, water-control structures, and conveyance and distribution systems typically are designed on the basis of design floods or droughts of different return periods and/or annual exceedance probabilities, which are derived from past failures and associated perceived degrees of tolerable risk and economic costs. Because there is a significant turnover in water management infrastructure, with considerable maintenance and major rehabilitation occurring in most countries about every 30 years, it can be expected that the operating capacity of such structures can be made to conform to evolving changes in climate. Analytical tools are available to provide the necessary degree of confidence in the design and operation of such systems in a reliable manner.

### *14.4.3. Impact on Flood Risk and Management*

Although the potential impact of global warming on the occurrence of flood disasters has been alluded to frequently in popular accounts of global warming, there have been very few studies addressing the issue explicitly. This is largely because it is difficult to define credible scenarios for changes in flood-producing climatic events (Beran and Arnell, 1995). Chapter 10 outlines the potential effects of global warming on riverine floods, and Chapter 9 reviews the effects of a rise in sea level and changes in storms on coastal flooding. This section considers the implications of changes in flood occurrence for flood risk and management. There are four major implications: a change in flood loss, a change in flood risk and the standard of service currently provided by flood management and protection schemes, a change in the cost of protecting against floods, and impacts on public and private financial institutions.

The effect of a change in the frequency of floods on flood losses has to be set against many other factors, including population growth, economic development, and expansion onto flood plains. These factors have large impacts, making it difficult to detect climate-related change on flood loss statistics.

It might be easier, however, to detect a change in the standard of service provided by existing flood management schemes. Flood protection works and flood plain land-use plans usually are based on either a risk analysis to determine the most cost-effective level of protection (balancing costs against benefits) or on some legislative or institutional guideline for standard of service. Urban-flood-protection works, for example, typically provide protection against floods with a return period of up to 100 years. A change in flood frequency characteristics can have a very significant effect on flood risk and hence standards of service: A small change in flood magnitudes can have a very large effect on the risk of a particular critical value being exceeded. Beran and Arnell (1995) have shown that, assuming statistical properties similar to those of British rivers, a 10% increase in the mean—with no change in the year-to-year variability of floods—would result in a current 10-year flood occurring on average once every 7 years.

Increased flood frequencies probably would lead to increased expenditures on flood management. Most directly, the costs of providing or improving structural flood defenses would increase; indirect costs to society also may be incurred if larger areas of potentially productive floodplain land are excluded from development by flood plain zoning policies. However, there have been no quantitative studies of the costs of maintaining flood protection in the face of global warming.

Finally, an increase in flood losses may place significant strains on public finances, if damages are covered by public funds, or on the insurance industry. The amount of aid provided varies from country to country, as does the amount of coverage provided by the insurance industry. At the global scale, the international insurance and reinsurance industry may be seriously threatened by the occurrence of a few large, closely spaced storm events.

The Mississippi floods of 1993 and the European floods of 1994/1995 triggered major reviews of flood management policies. It is unlikely that flood management in the 21st century will be similar to flood management in the 20th century; there will probably be an increasing emphasis on adopting nonstructural measures and coping with uncertainty in risk assessments. The future effects of global warming on flood risk and flood management therefore must be seen against this changing institutional and technical background.

## 14.5. Research Needs

Uncertainties and analytical difficulties confront attempts to quantitatively analyze the direct effects of global warming on water resources demands. Considerable research investment is required in order to improve prediction and adaptive responses in the face of these uncertainties and methodological problems, including:

- Uncertainties in GCMs and lack of regional specification of locations where consequences will occur
- The absence of information on future climate variability
- Uncertainties in estimating changes in basin water budgets due to changes in vegetation and atmospheric and other conditions likely to exist in the future
- Uncertainties in the future demands of each water sector
- Uncertainties in the socioeconomic and environmental impacts of response measures
- Water management criteria under a potential nonstationary climate
- Linkage of water and agricultural sectors through detailed study of the impact of climate change on irrigation
- The impact of land-use and land-cover changes on water management
- The role and impact on groundwater management and conjunctive use.

It is doubtful whether some of these uncertainties can be completely eliminated, and, as with anything in the future, unforeseen elements will arise.

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